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Abstract. Beta-decay branching ratios of ^{62}Ga have been measured at the IGISOL facility of the Accelerator Laboratory of the University of Jyväskylä. ^{62}Ga is one of the heavier T$_z$ = 0, $0^+ \rightarrow 0^+$ β-emitting nuclides used to determine the vector coupling constant of the weak interaction and the V_{ud} quark-mixing matrix element. For part of the experimental studies presented here, the JYFLTRAP facility has been employed to prepare isotopically pure beams of ^{62}Ga. The branching ratio obtained, BR = 99.893(24) %, for the super-allowed branch is in agreement with previous measurements and allows to determine the ft value and the universal $\mathcal{F}t$ value for the super-allowed β decay of ^{62}Ga.

PACS. 21.10.-k Properties of nuclei – 27.50.+e 59≤A≤89 – 23.40.Bw Weak-interaction and lepton aspects

1 Introduction

Nuclear β decay is a commonly used probe to study the properties of the atomic nucleus. As β decay is governed by the weak interaction, it may also be used to test the light-quark sector of the Standard Model (SM). The SM incorporates the conserved-vector-current (CVC) hypothesis, which assumes that the vector part of the weak interaction is not influenced by the strong interaction. Thus, the vector current should not be renormalized in the nuclear medium. The comparative half-life ft of a particular class of β-decaying nuclides gives access to the vector coupling constant g_v used to test CVC [1]. As a further test, the combination of g_v with the muonic vector coupling constant g_μ allows to determine the up-quark down-quark element V_{ud} of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix, which in the SM is unitary. V_{ud} has by far the most significant weight in such a unitarity test.

Due to their intrinsic simplicity, super-allowed $0^+ \rightarrow 0^+$ β decays (so-called pure Fermi transitions) are the preferred choice to determine the corrected $\mathcal{F}t$ values:

$$\mathcal{F}t = ft \times (1 - \delta_C + \delta_{NS}) \times (1 + \delta'_R) = \frac{k}{g_v^2 \times \langle M_F \rangle^2 \times (1 + \Delta_R)}$$

where k is a product of constants and $\langle M_F \rangle$ is the Fermi-decay matrix element $\langle M_F \rangle^2 = T(T{+}1) - T_{zi}T_{zf}$. T is the isospin of the decaying nucleus and T_{zi} and T_{zf} are the third components of T for the initial and final state, respectively.

The experimental quantities necessary for the determination of ft are: the β decay energy Q_{EC}, the half-life $T_{1/2}$, and the super-allowed branching ratio BR. The theoretical corrections δ_C, δ_{NS}, δ'_R and Δ_R must be determined by models [2, 3]. $\mathcal{F}t$ values have been determined for thirteen such super-allowed Fermi decays with a precision close to or better than 10^{-3} [1].

The latest determination of $\mathcal{F}t$ yields an average value of $\mathcal{F}t$ = (3071.4±0.8) s [3]. With the coupling constant for the purely leptonic muon decay, one determines $V_{ud} =$ 0.97418(26). Nuclear β decay provides the most precise determination of this matrix element, which dominates the unitarity test.

The main uncertainty in the determination of $\mathcal{F}t$ is due to the uncertainty in the nuclear structure dependent corrections $\delta_C - \delta_{NS}$, whereas the main uncertainty for the value of V_{ud} is due to the nucleus independent radiative correction Δ_R. Therefore, significant progress in this field demands improvements of these theoretical corrections. The radiative correction δ'_R could also be improved by adding more terms in its evaluation in the framework of quantum electrodynamics.

However, experimental data can still test the nuclear structure corrections $\delta_C - \delta_{NS}$. The experimental ft values corrected only with $(1 + \delta'_R)$ scatter significantly. When the nu-

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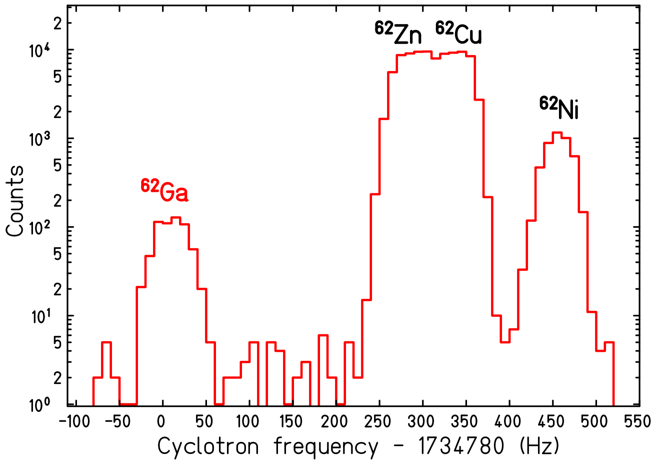

Fig. 1. Isobaric scan for A=62 with the purification trap of JYFLTRAP. The isobaric components are labeled and illustrated relative to the centre cyclotron frequency of ^{62}Ga (1734780 Hz). The trap multi-channel plate detector is saturated for ^{62}Zn and ^{62}Cu.

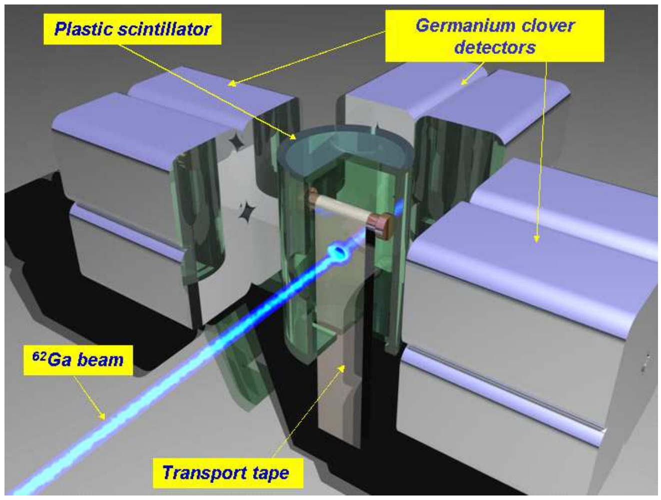

Fig. 2. Schematic drawing of the experimental set-up used in the present experiment. The activity is collected on a tape inside the 4π plastic scintillator (entrance hole diameter of 12 mm) viewed by two photomultipliers mounted on top of the scintillator (not shown) to detect β particles. The scintillator is surrounded in close geometry by three EUROBALL HPGe clover detectors for γ detection.

clear structure dependent term $\delta_C - \delta_{NS}$ is added, a constant $\mathcal{F}t$ value is found, thus verifying the CVC hypothesis and allowing for the determination of g_v and finally V_{ud}.

This test is particularly sensitive for large $\delta_C - \delta_{NS}$ corrections, which is the case for heavy T_z = 0 nuclei such as ^{62}Ga. In this work, we present a precision study of the β-decay branching ratios of this nucleus. Several β-decay branching ratio measurements for ^{62}Ga have already been published [4,5,6,7,8]. However, only the last reference [8] was able to observe and give branching ratios for transitions other than the 2^+ to 0^+ γ transition in ^{62}Zn and therefore to determine the β-decay feeding of several I^π = 0^+ and 1^+ states. The other quantities needed to determine the ft value, i.e. the β-decay Q value and the half-life, have been measured recently with high precision [6,7,9,10,11].

2 Experimental procedure

The experiment was performed at the IGISOL facility in the Accelerator Laboratory of the University of Jyväskylä. An intense proton beam (up to 45μA) at an energy of 48 MeV was directed onto a ^{64}Zn target of thickness 3 mg/cm^2. The fusion-evaporation residues recoiling out of the target were thermalised in a helium-filled chamber. A gas flow extracted the activity out of the target chamber. The singly-charged ions were then accelerated to about 30 keV and mass analysed by a dipole magnet with a resolution of m/Δm $\approx$ 300 and sent to the experimental setup.

We used two different schemes to perform the measurements: i) using the JYFLTRAP setup to separate ^{62}Ga from the other A=62 isobars. The JYFLTRAP consists of a radiofrequency quadrupole (RFQ) cooler [12] and of two Penning traps. In this case only the first trap, the purification trap [13], was used to separate ^{62}Ga from contaminants, which were mainly ^{62}Zn and ^{62}Cu having yields of more than 1000 times the yield of ^{62}Ga. The purification cycle was chosen to be as short as possible, in this case 71 ms, limited by the trap cleaning process employing the buffer-gas cooling technique [14]. This cycle time additionally sets the requirement for the accumulation time of A=62 ions in the RFQ. The isobaric cleaning scan for A=62 is shown in figure 1. To prepare clean ^{62}Ga samples, the cyclotron frequency was fixed to 1734780 Hz. The cleaned bunch was then ejected from the trap to a movable tape for decay studies. The collection tape (see below) was moved after 100 to 9000 of such cycles (this parameter was changed several times without any significant influence on the data). The ^{62}Ga rate was about 100 pps during beam-on periods.

ii) using a setup situated directly downstream from the IGISOL focal plane. In this scheme, we used two different measurement cycles. In the first, a grow-in time of 250 ms was followed by a decay period of 250 ms. The second had only a grow-in period of 390 ms. For both cycles, the grow-in was preceded by 10 ms beam-off time for background determination. At the end of the cycle, the collection tape was moved. The ^{62}Ga detection rate varied between about 50 and 120 pps during beam-on periods.

The detection setup consisted of a collection tape (100 μm thickness of mylar, half an inch wide), a 4π cylindrical plastic scintillator coupled to two 2-inch photomultipliers (PMs) and 3 HPGe clover detectors from the Euroball array with a relative efficiency of 120% per detector. This setup is shown schematically in figure 2. The collection tape was controlled by stepping motors which enabled a movement of about 10 cm in 100 ms, which was the chosen cycle time for the transport of the tape. The event trigger was a coincidence between the two PMs. The β-detection efficiency was determined with a calibrated ^{90}Sr source to be about 90%. The γ detection efficiency was determined with standard calibration sources (^{60}Co, ^{133}Ba, ^{134}Cs, ^{137}Cs, and ^{228}Th). Out of the 12 segments of the three clover detectors, two were rejected in the final analysis because their energy resolution (typically 3 keV for the good segments)

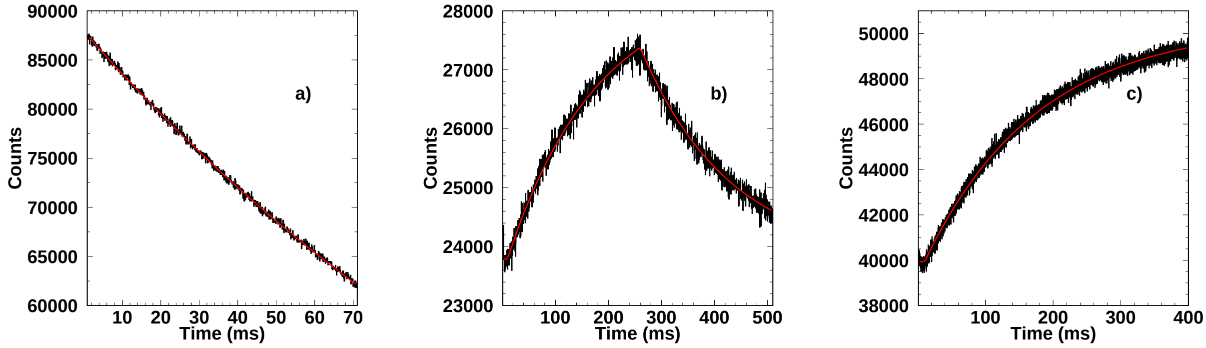

Fig. 3. Beta-decay time distributions determined by means of the plastic scintillator for the three different measurement schemes: a) trap-assisted spectroscopy using JYFLTRAP to prepare the pure ^{62}Ga sample. In this case only the decay component of ^{62}Ga is observed together with a constant background. The daughter activity is too weak and too long-lived to be observed. b) Time spectrum from the central IGISOL beam line, where a grow-in period of 250 ms was followed by a 250 ms decay time. The strongly produced contaminants ^{62}Zn and ^{62}Cu contribute to the constant background. c) After a 390 ms grow-in period, the tape was moved and a new cycle started. In b) and c), the cycles start with a 10 ms interval without beam. We integrated these time distributions to obtain the number of ^{62}Ga decays observed. The plots show the complete statistics of the different settings.

was rather poor (≈10-15 keV). The final γ detection efficiency was about 5.5% for the 954 keV γ ray of ^{62}Ga and 3.2% at 2227 keV in the add-back mode (see below).

Due to the rather close geometry of the detectors and the large β-decay Q value, the probability of β particles depositing energy in the germanium detectors was quite high (about 4% per crystal). Therefore, corrections to the γ-ray photopeak efficiency had to be applied in order to account for pile-up between a γ ray and a β particle in the decay of ^{62}Ga. This correction was obtained by means of a Monte-Carlo simulation which included the exact geometry and a realistic β spectrum. The average correction factor for the branching ratios in singles mode was 3.86(1)% and 12.85(1)% for the add-back mode (see below).

The data acquisition system was based on the GANIL data acquisition and allowed an online supervision of the experiment and an event-by-event registration of the events. The data were written on DLT tapes for further analysis.

3 Data analysis

We analysed the experimental data in two distinct ways: i) by treating the different segments of the clover detectors as independent detectors (singles analysis) and ii) by making use of the add-back mode, where we sum the signals from all crystals of a clover detector provided they were above the noise threshold (100 keV in the present case). Both analyses yielded similar results for the branching ratios of all γ rays observed. We also analysed the data from the different production schemes (with and without JYFLTRAP, grow-in only, grow-in and decay) independently. We obtained consistent results for all subgroups of our data.

The data obtained on the central beam line, i.e. without the JYFLTRAP system, are contaminated by other A=62 isobars and, to a much smaller extent, by A=63 isotopes. In particular, ^{62}Zn and ^{62}Cu were strongly produced and transmitted to the detection setup. The γ-ray spectra obtained during these measurements were strongly contaminated with γ rays from these isotopes. Therefore, we analysed the data in the following way: The intensities of the 954 keV γ ray which de-excites the first 2^+ state in the ^{62}Ga β-decay daughter nucleus ^{62}Zn and of the 851 keV line ($2^+_2 \to 2^+_1$) were determined directly from the β-gated γ spectrum. The other three γ rays at 1388 keV, 1850 keV and at 2227 keV, although to some extent visible also in the β-gated spectrum, were analysed in $\beta\gamma$-gated spectra, where the γ gate was the 954 keV γ ray.

This procedure prevents us from observing decays which by-pass the 954 keV level in ^{62}Zn. However, the background in the ungated spectrum was in any case too high to observe directly any other rather weak γ ray, not passing through the 954 keV level.

To determine absolute branching ratios, the source strength has to be known. The number of ^{62}Ga ions accumulated during the different measurement cycles was determined by fitting the time distribution of the β events registered with the plastic scintillator. As all events were triggered by this plastic scintillator, its own β detection efficiency is not needed.

To arrive at the final results, we averaged the results obtained by the different analysis procedures (singles and add-back). The error was determined by averaging the statistical error for each analysis and by adding quadratically the difference between the average value and the individual results.

4 Experimental results and comparison with results from the literature

Figure 3 shows the time distribution for the three different measurement cycles: a) the trap-assisted measurement with the Penning trap system JYFLTRAP, b) the measurement on the central IGISOL beam line with the grow-in and decay cycle, and c) the mesurement on the central beam line where we used

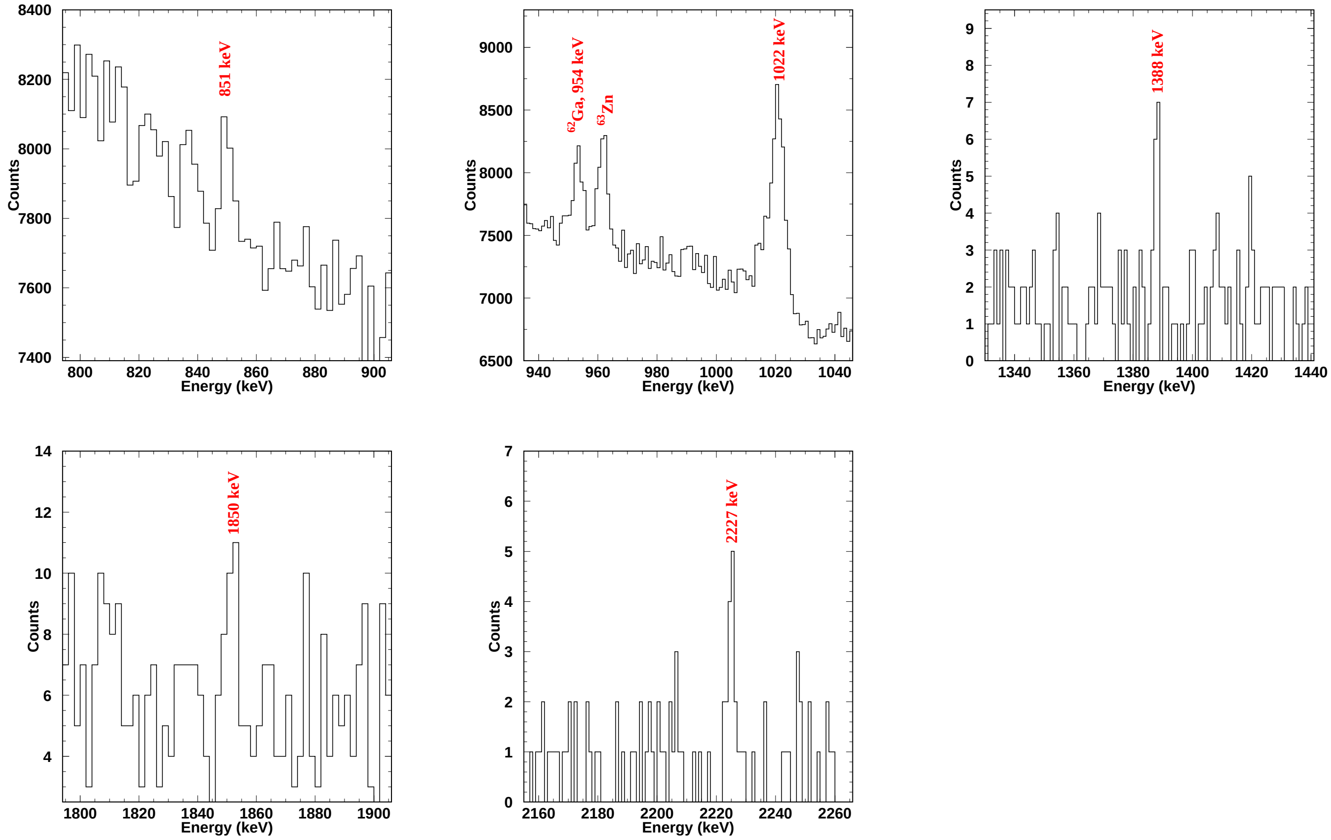

Fig. 4. Gamma-ray spectra in add-back mode (singles mode for the 1850 keV spectrum) showing regions of specific interest. The spectrum around the peaks at 851 keV and 954 keV are obtained only with a β-particle coincidence. The other spectra were taken in coincidence with the observation of a 954 keV γ ray. As the quality of the spectrum for the 1850 keV line obtained in singles mode is much superior to the spectrum obtained in the add-back mode, the singles-mode spectrum is presented here.

only the grow-in cycle. The integrated numbers of ^{62}Ga β decays observed during the different cycles are 4.3243(61)$\times 10^7$, 2.546(18)$\times 10^6$, and 2.4972(30)$\times 10^7$, respectively. To arrive at these results, the time distributions were fitted with the decay curve of ^{62}Ga, the grow-in and decay part, and the grow-in part only, respectively. For each fit, a constant was added for the background. The contribution of the contaminants and of the long-lived daughter nuclei was included in the constant background. Their explicit inclusion did not improve the fit.

As mentioned, the γ-ray branching ratios were determined by means of the singles and the add-back modes. Figure 4 shows the parts of the total γ-ray spectrum, where γ rays from the decay of ^{62}Ga were observed. The central upper figure shows the γ line due to the de-excitation of the first excited 2^+ state in ^{62}Zn. Using the total number of counts corrected for the γ detection efficiency at 954 keV and the β pile-up, we obtain a branching ratio for this γ ray of 0.086(9)%. For comparison, we give here the branching ratio we obtained in the singles mode (0.081(7)%) and the add-back mode (0.091(8)%). In table 4, we compare this result with branching ratios for this γ ray as found in the literature.

Four other γ rays already observed in the work of Hyland et al. [8] were identified in this work. They appear in the β-gated γ spectra (851 keV line) or in the spectrum additionally conditioned by the observation of a 954 keV γ ray and are shown in figure 4. The branching ratios determined for these γ decays are given in table 4. Their branching ratios compare reasonably well with the data obtained by Hyland et al. [8].

The result of interest is the branching ratio for the superallowed ground-state to ground-state decay of ^{62}Ga. It is evident from the results presented in table 4 that this branching ratio is of the order of 99.9%. We will use two approaches to determine this branching ratio more precisely.

A first approach is to use the calculated strength [1,15,16] which by-passes the first excited 2^+ state from a shell-model approach. This strength is calculated to be 20% of the observed decay strength of this 2^+ state. If we assume a 100% error for this value and take into account that the strength which by-passes the first 2^+ state is certainly not zero, we can adopt a value of 20^{+20}_{-10} % for this strength. When added to the observed strength from the 2^+ state, we obtain $0.108^{+0.029}_{-0.017}$% for all non-analog branches and an analog branching ratio of $99.893^{+0.018}_{-0.029}$%. With symmetrized uncertainties, our final result for this method is therefore 99.887(23)%.

As a second approach we follow the prescription of Hyland et al. [8], which uses the fact that 2^+ states are not fed directly

energy(keV)	Blank [4]	Döring et al. [5]	Hyman et al. [6]	Canchel et al. [7]	Hyland et al. [8]	this work
954	0.12(3)%	0.106(17)%	0.120(21)%	0.11(4) %	0.0809(33)%	0.086(9)%
851	-	-	-	-	0.0090(14)%	0.021(8)%
1388	-	-	-	-	0.0176(20)%	0.023(11)%
1850	-	-	-	-	0.0081(14)%	0.020(9)%
2227	-	-	-	-	0.0279(24)%	0.024(10)%

Table 1. Absolute γ-ray branching ratios obtained in the present work are compared to values from the literature. For the work of Hyland et al. [8], we show only the branching ratios of the γ rays also observed in the present work.

by the β decay of ^{62}Ga, but are fed from higher-lying 0^+ or 1^+ state. The missing feeding is therefore the difference between the observed decay strength of all 2^+ states and their feeding from above. From our data, we calculate a missing feeding of the first 2^+ state of -0.002(21)%, of the second 2^+ state of 0.021(8)%, and of the third 2^+ state of 0.020(9)% yielding a total missing feeding of 0.039(38)%. The strength which by-passes these three 2^+ states is, according to shell-model calculations [1,15,16], about 20% of the branching ratio of the 954 keV γ ray de-exciting the first 2^+ state. If we assume, as above, a 100% error for this value and take into account that the strength which by-passes the 2^+ states is certainly not zero, we can again adopt a value of 20^{+20}_{-10} % for this strength. With these values, we obtain the unobserved γ flux to the ground state of $0.010^{+0.018}_{-0.009}$%. Combined with the observed γ flux via the first excited state of 0.086(9)%, we obtain $0.096^{+0.028}_{-0.019}$% for the total non-analog strength and thus an analog branch of $99.904^{+0.019}_{-0.028}$% or, with symmetric error bars, 99.900(23)%.

This second result is in excellent agreement with the first one and we adopt a final super-allowed branching ratio of BR = 99.893(24)%. Our experimental results are summarised in figure 5.

Our value for the super-allowed branching ratio agrees reasonably well with the result obtained by Hyland et al. [8] of 99.861(11)%. The question is now how to average these two results to arrive at the final recommended value for the super-allowed branch. The problem is that in both determinations, in the present work as well as in the work of Hyland et al., the same shell-model calculations have been used to obtain the missing strength. We believe, however, that due to the fact that in both estimations a 100% error was assumed for these calculations, we can nonetheless average them. We finally obtain an average value of 99.867(10)%.

Another way of averaging the results from Hyland et al. and our results would be to average the γ branching ratios and then use these averages to calculate the total non-analog branching ratios according to the procedure proposed by Hyland et al. When we do so, we get a total missing strength for the 2^+ states of 0.025(7)% which has to be compared to the value of Hyland et al. of 0.024(6)%. Evidently, this yields the same final result for the non-analog and therefore also for the analog branching ratio. We prefer the procedure described in the previous paragraph, as it yields independent experimental final results which rely only on the same theoretical calculation. We therefore keep the final value for the analog branching ratio of 99.867(10)%.

With the half-life of 116.121(21) ms [17] as well as the Q value of 9181.07(54) keV [11] and the statistical rate function

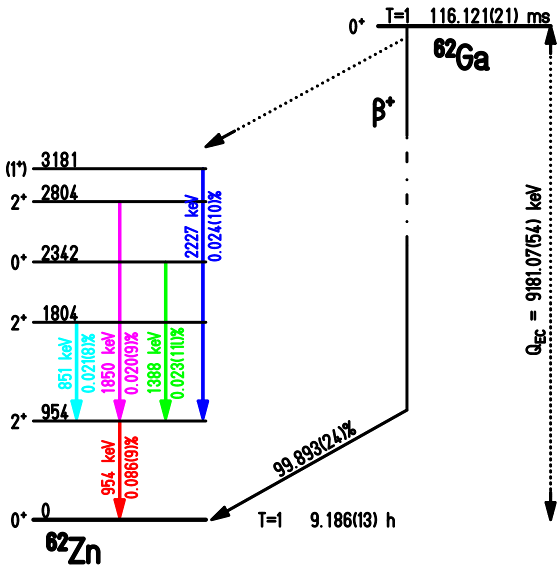

Fig. 5. Decay scheme of ^{62}Ga with the γ rays and their intensities as determined in the present work. Indicated in the figure is also the total Fermi-decay branching ratio, the ^{62}Ga half-life and the β-decay Q value.

of 26401.6(83), we obtain an ft value of 3074.1(12) s which includes the electron-capture correction. Using the correction factors as determined by Towner and Hardy [3], we obtain a $\mathcal{F}t$ value of 3071.4(72) s. This value compares well with the most recent evaluation [3] for the average $\mathcal{F}t$ value which yielded 3071.4(8) s and which included an $\mathcal{F}t$ value for ^{62}Ga.

5 Summary

We have determined the non-analog β-decay branching ratios of ^{62}Ga. The present experimental results together with shell-model calculations allowed the determination of the super-allowed analog branching ratio for the 0^+ to 0^+ ground-state to ground-state decay to be 99.893(24)%. The present result, although less precise, is in agreement with the high-precision study of Hyland et al. and enables the calculation of an error-weighted average value. Using published values for the β-decay half-life and the Q value, we determine a new ft value of 3074.1(12) s and a corrected $\mathcal{F}t$ value of 3071.4(72) s. The present value compares well with the average $\mathcal{F}t$ value obtained from 12 other nuclei.

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